

A life cycle assessment of residential waste management and prevention

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Abstract

Purpose The oft-cited waste hierarchy is considered an important rule of thumb to identify preferential waste management options and places waste prevention at the top. Nevertheless, it has been claimed that waste prevention can sometimes be less favorable than recycling because (1) recycling decreases only the primary production of materials, whereas waste prevention may reduce a combination of both primary and low-impact secondary production, and (2) waste prevention decreases the quantity of material recycled downstream and the avoided impacts associated with recycling. In response to this claim, this study evaluates the life cycle effects of waste prevention activities (WPAs) on a residential waste management system.

Methods This life cycle assessment (LCA) contrasts the net impacts of a large residential solid waste management system (including sanitary landfilling, anaerobic digestion, composting, and recycling) with a system that incorporates five WPAs, implemented at plausible levels (preventing a total of 3.6 % of waste generation tonnage) without diminishing product service consumption. WPAs addressed in this LCA reduce the collected tonnage of addressed advertising mail,

disposable plastic shopping bags, newspapers, wine and spirit packaging, and yard waste (grass).

Results and discussion In all cases, the WPAs reduce the net midpoint and endpoint level impacts of the residential waste management system. If WPAs are incorporated, the lower impacts from waste collection, transportation, sorting, and disposal as well as from the avoided upstream production of goods, more than compensate for the diminished net benefits associated with recycling and the displaced electricity from landfill gas utilization.

Conclusions The results substantiate the uppermost placement of waste prevention within the waste hierarchy. Moreover, further environmental benefits from waste prevention can be realized by targeting WPAs at goods that will be landfilled and at those with low recycled content.

Keywords Life cycle assessment · Municipal solid waste · Recycled content · Recycling · Waste management · Waste prevention

1 Introduction

The annual tonnage of municipal solid waste (MSW) generation is expected to almost double globally by 2025 (Hoonweg and Bhada-Tata 2012). In response to this expected increase and its accompanying environmental impacts, there have been widespread policy initiatives to increase waste prevention and diversion (e.g., European Commission 2005; US EPA 2006). This has created a need for life cycle assessments (LCAs) that account for the net impacts associated with all forms of MSW management, including waste treatment and prevention activities. Although often excluded from published LCAs of MSW, authors such as Coleman et al. (2003), Ekvall et al. (2007), Cleary (2010) and Nessi et al. (2013) have examined some of the methodological issues associated with

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incorporating waste prevention activities (WPAs) into this type of LCA. There has also been a notable increase in academic publications addressing this subject in the waste management and LCA literature in recent years (e.g., Cox et al. 2010; Gentil et al. 2011; Matsuda et al. 2012; Nessi et al. 2012; Salhofer et al. 2008; Sharp et al. 2010).

Claims of an important potential role for waste prevention in reducing the environmental impacts of waste management are relatively common (e.g., Gentil et al. 2011). However, studies of waste prevention potential, and LCAs addressing the effectiveness of waste prevention to reduce the environmental impacts of waste management systems, have not provided much substantiation for these claims. For example, the results of a study by Salhofer et al. (2008) indicated that the apparent potential of waste prevention measures to reduce waste generation in Vienna is relatively low. Those measures, addressing waste from advertising mail, beverage packaging, diapers, food waste, and “big events,” were capable of reducing the size of each waste stream by approximately 10 %, equal to 1–3 % of all municipal waste (Salhofer et al. 2008). Similarly, for a hypothetical European municipality, Gentil et al. (2011) observed that waste prevention had only minor direct consequences on the life cycle impacts of the waste management system.

Potential benefits of waste prevention are constrained by the amount of waste prevention that would be considered plausible or achievable without considerable effects on living standards. Indeed, several studies (e.g., Salhofer et al. 2008, Cleary 2010, Nessi et al. 2012) assume that WPAs should not reduce the consumption of product services. That assumption inherently restricts the types of waste prevention options that would be considered feasible for relieving pressure on waste management systems. One may compare within the LCA system boundary the various options addressed by the waste hierarchy, including WPAs and waste treatments, so that they are regarded as functional equivalents in managing MSW. Cleary’s (2010) Waste Management and Prevention (WasteMAP) LCA is such a conceptual model, although it has not yet been applied to a residential waste management system.

The estimated benefits of WPAs are influenced by the method employed to depict waste prevention and recycling within LCA. Relative to recycling, it appears obvious that avoided production and consumption would always result in superior environmental outcomes. However, results from the US EPA’s (2006) Waste Reduction Model (WARM) indicate that recycling may sometimes be responsible for lower net greenhouse gas emissions than avoiding product consumption. This seemingly odd finding is a consequence of the assumption that recycled material displaces virgin material, whereas waste prevention avoids the production of a combination of both virgin and recycled materials (US EPA 2006). Furthermore, an LCA by Gentil et al. (2011) inherently

assumes that waste prevention would diminish the net benefits from recycling due to the reduction in recycling feedstock.

Upstream, waste prevention reduces demand for reprocessed material. Downstream, it shrinks the supply of material available for recycling. For generic product LCAs with closed-loop recycling, there need not be a discrepancy between the assumed recycled content in a product and the recycling rate of that product (excluding the effect of processing losses). However, LCAs of waste are generally undertaken at a municipal scale (Cleary 2009), which makes it far more likely that such a discrepancy exists. The proportion of recycled content in goods and the proportion of these same goods that is recycled do not match due to imports/exports, open-loop recycling, and multiple types of products containing recycled content from the same source (e.g., input of glass bottles, output of glass bottles and fibreglass). There is yet to be an LCA of waste which takes into account the discrepancy between the average recycled content of a product subject to a WPA and the local recycling rate of that same product.

The City of Toronto, Canada, with a population of approximately 2.5 million, exemplifies a municipality which includes some WPAs (backyard composting and grasscycling) in its calculation of the quantity of waste diverted from landfills (FCM 2004). Indeed, waste diversion is considered a prime indicator of the success of Toronto’s MSW management system (City of Toronto 2007). Educational programs and financial incentives have been employed to promote WPA adoption, such as the “City of Toronto Municipal Code Chapter 604, Packaging,” which required retailers to charge five cents or more for each plastic shopping bag supplied to customers (City of Toronto 2011).

The waste prevention goals of the City of Toronto make it an ideal case study for an LCA of residential waste management using the system boundary and functional unit assumptions specified in the WasteMAP LCA model (Cleary 2010). As LCA research pertaining to waste prevention is relatively uncommon (Saner et al. 2012), the following study is a response to this dearth of information about the environmental impacts of residential waste management systems that incorporate waste prevention.

2 Methodology

2.1 Residential waste management scenarios

This study compares two LCA scenarios. The first scenario (S1) depicts the City of Toronto’s residential waste management system in 2008, whereas the waste prevention scenario (S2) incorporates into this system five WPAs, each selected to exemplify the main types of WPAs listed in Cleary (2010) (Table 1). The comparative results are used to assess the potential of a broad set of WPAs to reduce the net life cycle

impacts of this urban waste management system. As in Gentil et al. (2011), the LCA scenarios depicted use average data (e.g., average electricity mix) within the LCA unit processes, including displaced electricity.

2.2 Functional units

The LCA functional units not only ensure a consistent amount of residential waste managed in all scenarios, but also maintain identical reference flows of functionally equivalent product services for municipal residents. The primary functional unit is the mass of the City of Toronto's residential waste that was managed in 2008. Managed waste is defined as the tonnage collected by the municipality and through the wine/spirit packaging deposit-return program, as well as the net tonnage prevented due to the WPAs listed in Table 1.

Secondary functional units (SFUs), which are used only in S2, quantify the service substitutions associated with the WPAs (Cleary 2010). The disposable bag WPA has an SFU of 1.19×10^8 bags. The SFU for the newspaper WPA depicts the total amount of time spent reading newspaper articles (1.70×10^7 h) online instead of in printed format. For the wine/spirit packaging WPA, the SFU addresses the volume of packaged wines and spirits subject to the packaging substitutions (3.27×10^7 l). SFUs are not required for the admail and grasscycling WPAs because no product services are consumed (i.e., the admail and grass are unwanted).

2.3 System boundaries

Although the “cradle” of the S1 life cycle is set at the moment of residential waste generation, the system boundary of S2

Table 1 Waste prevention activities addressed in the waste prevention scenario, the properties of each type of WPA and the tonnage of waste prevention

Waste prevention activities (WPAs)	Type of WPA (based upon Cleary 2010)	Description of WPA and quantity of waste prevention
<i>AdMail WPA</i> Reduced generation of unaddressed advertising mail	Reduction in material consumption without product service substitution	Reduced generation of weekly advertising flyer packages, equal to the difference between the 2 % already opting out of admail, and the 67 % of Canadians who find admail to be of no interest [11,793 tonnes of prevented newsprint waste]
<i>Disposable bag WPA</i> Reuse of disposable carry-out plastic shopping bags	Reuse of a disposable good	Reuse of an additional 20 % of disposable carry-out plastic shopping bags [831 tonnes of prevented HDPE waste]
<i>Newspaper WPA</i> Substitution of articles available online for those printed on newsprint	Substitution of a service for a disposable good	Substitution of articles available online (via a desktop computer) for those printed on newsprint, resulting in the prevention of an additional 10 % of newsprint from Toronto daily subscription newspapers [4,528 tonnes of prevented newsprint waste, and 10 tonnes of additional computer equipment]
<i>Wine/spirit packaging WPA</i> Substitution of refillable glass bottles (RFGs) for conventional single use (CSU) wine and spirit bottles	Substitution of a reusable good for a disposable one	Refillable glass (RFG) bottles are substituted for all 750, 1,000, and 1,500 ml containers for Canadian and bulk imported wines in 2008, as well as 750 and 1,140 ml containers for Canadian and bulk imported spirits
Substitution of lightweight single use (LSU) glass bottles, PET plastic bottles, and aseptic cartons (ACs) for conventional containers	Lightweighting of a good	(1) Aseptic cartons (ACs) are used to package 10 % of the 2008 volume sales of imported packaged wines in 1,500 ml containers, and 50 % of the 2008 volume sales of imported packaged wines in 1,000-ml containers (2) PET bottles replace 10 % of the 2008 volume sales of imported packaged spirits in 750 and 1,140 ml containers, and 50 % of the 2008 volume sales of imported packaged spirits in 200, 375, 1750, and the remaining container sizes (3) The remaining containers, excluding RFG bottles, are packaged in lightweight single use (LSU) bottles (assumption of 20 % lower mass than CSU containers, for all container sizes) [9,248 net tonnes of prevented packaging wine and spirit packaging waste, based on Cleary (2013)]
<i>Grasscycling WPA</i> Grasscycling	On-property residential waste treatment	An additional 5 % of the mass of yard waste is prevented due to grasscycling [4,028 tonnes of prevented yard waste]

comprises both upstream and downstream components. Modeled processes for the downstream components of both scenarios include waste collection from residential dwellings, the sorting of the recyclable material, the shipping of the waste to the recycling, biological treatment and landfilling facilities, and the treatment and disposal of the waste. The LCA system boundary also incorporates avoided impacts associated with the recycling of waste as well as the electricity displaced due to landfill gas utilization. Therefore, waste prevention, by reducing inputs for recycling and landfilling, decreases the potential benefits from these avoided impacts.

The upstream system boundary (S2 only) comprises processes associated with the generation of the waste materials targeted for prevention, as well as the substitute product systems that generate less waste. For the admail and newspaper WPAs, the upstream system boundary encompasses raw material acquisition and the manufacture and transport of newsprint. The newspaper WPA also addresses the production and use of desktop computers, including the electricity required to download data from the internet. The disposable bag WPA includes raw material extraction, the processing of high density polyethylene (HDPE) into bags, and the transportation of these bags to the retailer. Finally, the wine/spirit packaging WPA takes into account raw material extraction, processing, transportation, and packaging manufacture. When addressing refillable wine and spirit bottles, the system boundary comprises the bottle cleaning process, as well as the shipping of used glass bottles to and from the retailer and the cleaning/refilling facilities. The wine and spirit container wastes collected through the deposit-return/stewardship program are included in both scenarios because they are affected by the WPAs in S2.

The LCA scenarios exclude WPAs already implemented (i.e., not considered “additional”), such as backyard composting. Avoided impacts resulting from the use of the compost from biological waste treatment are considered negligible because it is uncertain if, had the compost not been produced, consumers would have purchased a substitute material. Furthermore, upstream recycling processes (e.g., from the recycling of glass containers broken during the filling process) are also excluded from the system boundary because they are a component of industrial waste management. A complete description of the LCA unit processes included within the system boundary is located in Section 4 of the paper and Section S-4 of the Supplementary Material.

2.4 Selection of the avoided burden approach

The ISO (2006) has claimed that, in closed-loop recycling, allocation is not required because “the use of secondary material displaces the use of virgin (primary) materials.” Therefore, in keeping with this preference for system expansion instead of allocation, the avoided burden approach

(Frischknecht 2010) is selected in order to incorporate within the LCA system boundary the avoided impacts resulting from waste prevention, recycling, and displaced electricity. Although this approach is commonly used when depicting recycling and displaced electricity, its application to waste prevention has been unclear, especially if the prevented waste includes recycled content. In this LCA, it is assumed that the reduction in available feedstock for recycling would necessitate additional production using virgin sources.

2.5 Data sources, life cycle assessment software, and impact assessment tools

This LCA is undertaken using *SimaPro* 7.3.3 LCA software. Sources of profile input and unit process data include field research undertaken by the author, published and unpublished government and industry information and statistics, as well as peer-reviewed literature. Primary profile input data for the downstream unit processes include waste composition and tonnage, transportation distances, and the flows of waste to the various waste treatment and disposal facilities. The unit processes specific to each scenario are adaptations of those from the *USEcoinvent (US-EI)* (version 2.2) (Earthshift 2013) LCA database. Furthermore, the following unit processes were created by the author and are based on data from both primary and secondary sources: (1) anaerobic digestion of source-separated organic waste, (2) aseptic carton manufacture, (3) bottle washing, (4) glass production and recycling, (5) HDPE recycling, (6) PET recycling, and (7) the sorting of recyclable material (Section S-4.2, Supplementary Material). Each LCA scenario comprises a unique combination of unit processes that represent those processes within the LCA system boundary. The unit processes included within the S1 and S2 system boundaries are used for estimating the life cycle inventory of each waste management scenario (further detail is available in Section 4, and Section S-4 in the Supplementary Material).

The impact assessment stage of the LCA uses the *ReCiPe* (version 1.06) life cycle impact assessment (LCIA) method (Goedkoop et al. 2009), one of the most recent and comprehensive LCIA methods available which includes both midpoint and endpoint level indicators. Its hierarchist perspective (Europe H/A) is employed because it is “based on the most common policy principles with regards to time-frame and other issues” (Goedkoop et al. 2009). However, in order to supply a range of interpretations of impact assessment results using identical LCA process inputs, the results are also calculated using the two alternative *ReCiPe* perspectives (egalitarian and individualist). *ReCiPe*’s egalitarian (E) perspective is considered precautionary, taking into account longer timeframes, while the individualist (I) perspective reflects short-term interest and technological optimism (Goedkoop et al. 2009). The climate change midpoint indicator exemplifies

the differences between these perspectives. This indicator has a 20-year time horizon under the I perspective, expanding to 100 and 500 years when adopting the H and E perspectives, respectively.

In the sensitivity analysis, the midpoint level LCIA results using *ReCiPe* are also contrasted with those calculated with the *TRACI 2.1* (version 1.00) LCIA method (Bare et al. 2003) employing the US/Canada 2008 normalization/weighting set. *TRACI*'s relatively low number of midpoint impact categories (ten), and its lack of endpoint impact indicators limit the detail of the results analysis using this LCIA method. In comparison, *ReCiPe* has 18 midpoint impact categories.

3 Mass balance

Figure 1 illustrates the waste flows within the two LCA scenarios, while Table 2 lists the tonnage of each numbered flow. Since the WPAs affect the amount and composition of waste to be treated, it is assumed that the proportions of each waste stream that were landfilled, recycled, and biologically treated are identical to the proportions in the 2008 reference year.

Data from the City of Toronto (2008, 2010a, b), Waste Diversion Ontario (WDO) (2008) and the Stewardship Ontario (2006a, b) waste audit program are used to estimate the tonnage of residential waste generated, collected, and treated. The overall quantities collected and treated are supplied by the city. The material composition of the residual waste for landfilling is estimated by extrapolating data from published waste audits of single family and multiple unit dwellings in Toronto in 2005 and 2006 (Stewardship Ontario 2006a, b). WDO data are used to estimate the material composition of the recyclable wastes collected (see Section S-2 of Supplementary Material for detail on the procedures

used to estimate the material composition of the residual and recyclable wastes).

3.1 Admail WPA

The advertising mail (admail) WPA, which addresses weekly advertising flyer packages, is selected as a measure to reduce the production of unwanted products that generate waste. For a plausible estimate of the potential for decreasing the amount of admail, both the level of admail refusal and the percentage of the population that does not wish to receive this material are taken into account. Some voluntary initiatives have been introduced in North America to foster reduced admail consumption, including admail opt-out provisions by Canada Post (n.d.). However, these initiatives have not been successful in reducing admail to an extent comparable to the surveyed percentage of the Canadian population who find this advertising to be of no interest, which has been estimated at 67 % (FDSA 2007). According to Canada Post (2007), only two percent of Canadians have opted out of receiving admail. For this WPA, it is assumed that the current refusal percentage for admail is identical to Canada Post's admail opt-out percentage, since the sign objecting to admail that must be posted on one's mailbox would presumably be seen and obeyed by the private carriers of admail as well. The amount of waste prevention depicted by the admail WPA is based on the difference between the 2 % already opting out of admail, and the 67 % of Canadians who find admail to be of no interest. This difference is equal to 11,793 t, based on a 350 g estimate of the average mass of an advertising flyer package delivered weekly to Toronto's 996,893 households (WDO 2008). The 350 g estimate was generated in consultation with the circulation manager of the largest flyer distribution company in the city (D. Umpleby, pers. comm.).

The assumed quantity of admail waste prevention undertaken in S2 (4.7 kg/capita/year) is comparable to the estimate

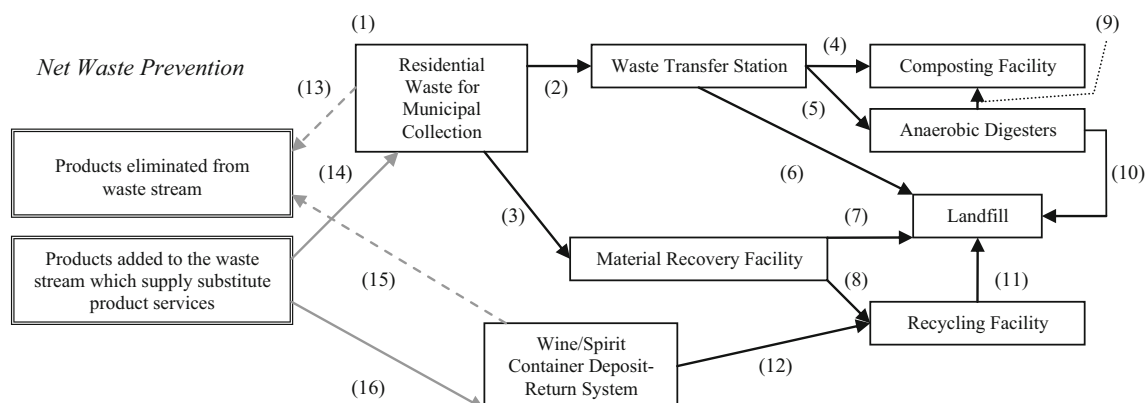


Fig. 1 Flows of waste under the LCA scenarios of the City of Toronto's residential waste management system. *Dashed arrows* represent negative flows of waste. *Double-lined boxes* and *grey arrows* represent systems

and flows exclusive to scenario 2. The magnitudes of the waste flows associated with each waste flow identifier are defined in Table 2

Table 2 Mass of waste flows associated with each waste management scenario

Stage of life cycle		Mass of waste (tonnes) ^b	
Waste flow identifier ^a	Description	2008 reference scenario	Waste prevention scenario
1	Residential waste for municipal collection	830,253	806,251
2	Waste to transfer stations	830,253	806,251
3	Waste to material recovery facilities (MRFs)	191,261	176,937
4	Waste from transfer stations to composting facilities	82,766	78,738
5	Waste from transfer stations to anaerobic digestion facilities	117,751	117,751
6	Waste from transfer stations to landfills	470,989	462,904
7	Waste from MRFs to landfills	32,514	30,079
8	Waste from MRFs to recycling facilities	158,747	146,858
9	Waste (digestates) from anaerobic digestion facilities to composting facilities	94,201	94,201
10	Residual waste from anaerobic digestion facilities to landfills	23,550	23,550
11	Contaminants from recycling facilities to landfills	4,340	4,081
12	Waste from wine/spirit container deposit-return system to recycling facilities	13,439	7,023
13	Prevented waste that would have been collected by the municipality for treatment	0	–27,465
14	Additional waste (for municipal collection) from goods supplying substitute product services	0	3,463
15	Prevented waste that would have been collected through the deposit-return system for treatment	0	–13,439
16	Additional waste (for deposit-return system) from goods supplying substitute product services	0	7,023

^a Waste flow identifiers refer to each waste flow arrow from Fig. 1

^b Although in the model the waste prevention and collection estimates are rounded to the tonne, the specific numbers of digits associated with all of these estimates are not intended to indicate a particular level of certainty

of 5.7 kg/capita/year by Salhofer et al. (2008) which depicts the quantity of unwanted admail in Vienna, Austria. The per capita estimate by Salhofer et al. (2008) takes into account the results of a survey by Wassermann et al. (2004) which indicated that less than half (47 %) of households in Vienna, Austria wished to receive admail. Unlike in Salhofer et al. (2008), the unwanted admail estimate in S2 excludes admail from postal carriers and advertising flyers within subscription newspapers.

3.2 Disposable bag WPA

The disposable bag WPA depicts the reuse of carry out disposable plastic bags. These bags had been targeted for waste prevention through the Ontario Plastic Bag Reduction Initiative, a voluntary agreement between government, industry and the Recycling Council of Ontario to reduce the number of plastic bags distributed in the province of Ontario, Canada by 50 % by 2012 (Ontario Plastic Bag Reduction Task Group 2008). Although much of this waste prevention would be a consequence of the substitution of reusable bags, an increase in the reuse level of disposable bags is also a possibility. Most disposable bags in Canada are already used two or more

times (CPIA n.d.), frequently as garbage bags, and 90 % of disposable bags are reused, according to a poll commissioned by the Canadian Plastics Industry Association (Exchange Magazine 2006). In comparison, waste audits conducted by Stewardship Ontario in 2009 have indicated that 56 % of plastic bags were reused as containers for garbage, source-separated organics or recyclables (Ontario Plastic Bag Reduction Task Group 2010). In light of these data, as well as the lack of published information on the current levels of disposable bag reuse in stores, this WPA is based on an estimate that an additional 20 % of disposable plastic bags are displaced through the reuse of these types of bags in stores. This reuse in stores needs not affect the levels of plastic bag reuse in the home, since the bags would presumably remain intact.

The Ontario Plastic Bag Reduction Task Group (2010) has claimed that approximately three billion disposable plastic bags were distributed in Ontario in 2008. Accounting for the percentage of Ontario's population living in Toronto (19.76 %) and the average mass of 7 g per bag (Verghese et al. 2009, CPIA n.d.), the disposable bag WPA is estimated to prevent the generation of 831 tonnes of waste.

3.3 Newspaper WPA

The newspaper WPA depicts the replacement of daily subscription newspapers with their online equivalent. The consumption of newsprint from newspapers has fallen steeply in recent years, reflected by annual contractions in the Ontario newspaper market of 12.5 % in 2008 and 7.5 % in 2009 (Canadian Newspaper Association 2010). Much of this reduced consumption could be attributable to the substitution of online newspaper articles for newspapers. Based on the mean of the 2008 and 2009 newspaper market contractions, an additional 10 % reduction in the consumption of daily subscription newspapers from the 2008 levels is assumed, equal to 4,528 tonnes of waste prevention.

Field research (described in Section S-1.1 of the Supplementary Material) was undertaken in order to supply estimates of the average mass of each of the four daily subscription newspapers read in the City of Toronto on each day of the week. The resulting estimates were multiplied by the total number of newspapers of each particular publication that were sold on the given day of the week in 2008, based on circulation data from the Canadian Newspaper Association (2009).

3.4 Wine and spirit packaging WPA

The wine/spirit packaging WPA is based on an LCA by Cleary (2013) addressing alternative packaging systems for wines and spirits consumed domestically (i.e., outside of commercial establishments) in the Toronto market in 2008. For the refillable bottle component, domestic and bulk imported wines and spirits are assumed to be packaged in refillable glass containers, representing one third of the wine/spirit market (excluding wine in bag-in-box containers) by volume. The substitution of lightweight single use glass bottles, PET bottles, and aseptic cartons affects the remaining two-thirds of the Toronto wine/spirit market by volume. Changes in the quantities and types of closures, capsules, and labels used are addressed in this WPA as well. The justifications for the assumptions used for the wine and spirit packaging WPA are described for the alternative packaging scenario in Cleary (2013).

3.5 Grasscycling

The City of Toronto (2008) estimates that grasscycling resulted in a 15 % reduction in the tonnage of yard waste collected in 2008. The Generally Agreed Principles (FCM 2004) that the City of Toronto uses to calculate waste flows assumes an absolute limit of 20 % of yard waste prevention from grasscycling, a limit which is attained once a “ban on grass in yard waste and garbage streams, a three-bag limit or less, with user-pay on extra bags, and a promotion and education program” is implemented. This type of system was not in

place in Toronto at the time. For the grasscycling WPA, the 20 % level is adopted, which is equal to an additional 4,028 tonnes of grasscycling.

4 LCA unit processes

The LCA unit processes in the two waste management scenarios are adaptations of those derived from the *US-EI* database (Earthshift 2013), as well as processes defined using data acquired from published peer-reviewed literature, equipment manufacturers, and operators. The electricity mixes of the foreground unit processes are replaced with those more representative of their geographical contexts. Specifically, substitutions were made to account for the average electricity supply mix from the 2008 national electricity transmission grid of the country where each process took place (IEA 2008). Those processes occurring in Canada use the 2008 Ontario electricity supply mix (53.0 % nuclear, 24.1 % hydro, 14.5 % coal, 6.9 % natural gas, 0.9 % wind, 0.6 % other—IESO 2009). Unit process inputs for infrastructure components (e.g., waste collection vehicles) of the foreground unit processes continue to use the standard US electricity mix from the *US-EI* database. A comprehensive list and description of those unit processes selected for the LCA scenarios is available in Section S-4 and S-5 of the Supplementary Material and in Cleary (2013).

4.1 Upstream processes

4.1.1 Admail WPA

Advertising mail is modeled as newsprint with a 40 % recycled content (Section S-4.4, Supplementary Material). This conservative estimate is based on the minimum recycled content of newsprint used for the Toronto Star (Toronto Star n.d.), the daily newspaper with the largest circulation in Canada (Canadian Newspaper Association 2010). This percentage is considerably lower than the City of Toronto's 66 % recycling rate for paper, a waste stream which includes newsprint.

A 541 km average transport distance from the paper mill to the City of Toronto is assumed, based upon the average distance from Toronto to the three sources of newsprint for the Toronto Star. Its newsprint is derived from mills in Trois-Rivières, Quebec (673 km from Toronto), Kapuskasing, Ontario (831 km), and Thorold, Ontario (120 km) (Toronto Star n.d.). From an analysis of Statistics Canada 2003 and 2004 data undertaken by Travacon Research Limited (2007) in its report for the Forest Products Association of Canada, it was estimated that 75 % of Canadian pulp and paper is shipped by rail, with the remainder by truck. This modal split is adopted

for calculating the emissions from the transportation of newsprint.

4.1.2 Disposable bag WPA

The disposable plastic shopping bags addressed in this WPA are modeled as HDPE plastic with a 15 % recycled content, based on ICF Consulting's (2005) recycled content estimate for HDPE in Canada. The municipal recycling rate for plastic film (<1 %), including plastic shopping bags, is far lower than the assumed level of recycled content in the disposable bags. There are no published data on the mean shipping distance of disposable plastic bags from the manufacturer to retailers in Toronto. Therefore, the relatively short trucking distance of 100 km is adopted because the Greater Toronto Area is the largest manufacturing centre of Canada and it would be unlikely that the 426 km transport estimate used for Canada by ICF Consulting (2005) in its GHG LCA of Canadian industries would be valid for this LCA.

4.1.3 Newspaper WPA

The newsprint production and transportation assumptions for the newspaper WPA are identical to those for the admail WPA. However, unlike in the admail WPA, a functionally equivalent substitute for the prevented product must also be taken into account. As in Moberg et al. (2010), the time spent reading newspaper articles is adopted as the means of measuring the use of the product service (i.e., provision of knowledge derived from reading newspaper articles). This time period is calculated by (1) multiplying the number of newspapers prevented by the number of readers per copy, and (2) multiplying the result by the average time each reader spends reading the newspaper articles. The newspapers are assumed to have an average readership of 3.18 readers per copy, based on research from Scarborough Research and Newspaper National Network LP (2010) pertaining to the readership of the top 25 newspapers in the United States in 2008. It is also estimated that the average person who reads a newspaper in print or online reads it for 20 min per day, the average of the 30-min estimate by Moberg et al. (2010) and the 10-min estimate of Hirschler and Reichart (2003).

In order for the waste management system to maintain equivalent SFUs, it is necessary to replace the time spent to read a printed newspaper with the equivalent amount of time spent reading downloaded newspaper articles displayed on a computer monitor. The time use estimate is entered into the "use, computer, desktop with LCD monitor, active mode" US-EI unit process. This unit process excludes the amount of electricity used to download newspaper content. Therefore, a supplemental unit process is created, with its inputs based on the estimate that 7 kWh/GB were required to transmit downloaded content in 2008 (Weber et al. 2010), and the

assumption by Moberg et al. (2010) that online articles comprise 5 MB of downloaded content per reader per day. While impacts from the production and disposal of the 10 tonnes of additional computer equipment are taken into account, those from the production and maintenance of internet servers and networks are excluded and assumed negligible.

4.1.4 Wine and spirit packaging WPA

All assumptions pertaining to the production and transportation of the wine/spirit containers and secondary materials are derived from the municipal scale LCA of wine and spirit packaging in Cleary (2013). The main data inputs for the unit processes are based on statistics from the Liquor Control Board of Ontario (2008), Statistics Canada (2008a, b), the Association of Canadian Distillers (2008) and the Canadian Vintners Association (2008). Refillable bottles for domestic wines and spirits are modeled using the estimate generated by *The Beer Store* (TBS 2009) that refillable containers are used an average of 15 times. A 100 km average trucking distance between the refillable container collection centers in Toronto and the bottling/washing/refilling facilities is based on Cleary (2013). Transportation data and assumptions for nonrefillable containers are derived from Statistics Canada (2008b) import statistics as well as questionnaires to wineries and distilleries (Cleary 2013). The levels of recycled content in Canadian glass containers are 55 % (brown glass), 58 % (clear glass), and 75 % (green glass) (Magaud et al. 2010), while the recycled content of PET containers is considered negligible (Cleary 2013, based on statistics from NAPCOR 2008). In comparison, the overall recycling rate of glass wine/spirit containers from Toronto, including both the municipal and TBS programs, is estimated to be 81 %. PET bottles and aseptic cartons for wines/spirits are estimated to have recycling rates of 61 % and 43 %, respectively (including recycling via the municipal and TBS programs).

4.1.5 Grasscycling

Unlike the other WPAs, grasscycling affects only the downstream component of the waste management system, and reduces the quantity of yard waste collected and treated. It is assumed that no new equipment, such as a mulcher, would be necessary in order to increase the level of grasscycling by 5 %.

4.2 Downstream processes

4.2.1 Residential waste collection and transportation

In Toronto, the collection of source-separated organic (SSO) waste occurs once per week, while recyclables and residuals (garbage) are collected in alternating weeks. Unpublished data

acquired from the City of Toronto (2010a) to estimate waste transportation emissions include the following: (1) the city to which each type of residential waste material was sent in 2008; (2) the approximate proportions of each type of residential waste stream sent to each treatment/disposal facility in 2008; and (3) the average distances that Toronto's waste collection/transfer vehicles transported waste (Section S-3.1, Supplementary Material). Impact estimates also account for the fuel use and average load of the waste collection and transfer vehicles, and the processes associated with the production of these vehicles (unit processes listed in Section S-4.1, Supplementary Material).

4.2.2 Sorting

Once collected, residential waste is shipped either to waste transfer facilities or to material recovery facilities (MRFs). At the MRFs, recyclables are sorted before they are sent to the processors. In 2008, Toronto's MRFs produced a 17 % residue from the recycling materials collected at curbside and received for processing, all of which was landfilled (City of Toronto 2010a). An author-defined unit process for sorting includes MRF energy inputs based on Franklin Associates (2010), and the material (nonwaste) and capital inputs specified in the *US-EI* process entitled "waste paper sorted, for further treatment" (Section S-4.2.3, Supplementary Material).

4.2.3 Biological treatment

Toronto's organic waste is classified into yard waste (including Christmas trees) and SSO waste streams. The former is composted while the latter is subject to both anaerobic digestion and composting once the waste is processed to remove contaminants. The resulting compost from both types of organic waste is then used for farms and parks (City of Toronto 2010b), as well as for private gardens (City of Toronto 2011).

The *US-EI* unit process for composting is used to depict the treatment of yard waste and SSO digestates, while the LCA process concerning the anaerobic digestion of the SSO waste is author-defined. Unit process inputs are based upon the 2008 operating records for Toronto's Dufferin Organic Processing Facility (Section S-4.2.1, Supplementary Material). SSO treatment undertaken at the Dufferin facility, which received approximately 40 % of the City's SSO waste in 2008 (City of Toronto 2010a), is also assumed to be representative of that taking place at the remaining SSO processing facilities.

The 37.5 % reprocessing efficiency estimate of Rigamonti et al. (2009), which depicts the composting of organic waste, is used for calculating the mass of compost generated from the yard wastes. In contrast, additional material losses from composting the SSO waste digestates are assumed negligible because anaerobic digestion already results in the

decomposition of most of the material inputs, while stabilizing much of the remaining mass.

4.2.4 Recycling

In keeping with ISO (2006) standards for LCA, this LCA depicts recycling as the impact difference between the waste recycling process and the production of goods composed of only virgin content. The *US-EI* database applies the cut-off allocation for recycling, which excludes recycling processes from the LCA system boundary, including any avoided burdens (Doka 2009; Earthshift 2013). This database often lacks the unit processes for recycling, making it necessary for the user to either define the processes from industry data, or use alternative databases. For certain recycling streams, the documentation for the database provides suggestions for selecting the avoided product and the "input from technosphere." For others in which there are no suggested processes (or the suggested substitute processes are deemed highly questionable in the database documentation), it was necessary to use some unit processes from the *Franklin USA 98* database (Norris 2003) or define processes based upon a Franklin Associates LCA from 2010. Although the given unit processes in the LCA databases mostly depict recycling in terms of the quantities of new materials generated that include recycled content (e.g., kg of polystyrene produced with 50 % recycled content), this LCA addresses recycling processes relative to the quantities of recycled material inputs used (e.g., kg of waste polystyrene inputs into the polystyrene production process).

Due to the considerable losses of recyclable material during the reprocessing procedure (Rigamonti et al. 2009), as well as the presence of contaminants within the waste stream, it is inappropriate to assume a mass substitution ratio of 1:1 for the recyclable waste inputs and the material outputs. The recycling unit processes for each waste material take into account the presence of contaminants and losses during reprocessing. Moreover, recycling processes often require inputs of both waste material and virgin material. For example, the *Franklin USA 98* (Norris 2003) unit process for polystyrene (PS) recycling assumes that 500 lb (227 kg) of waste PS inputs (plus 50 lbs of processing losses from these waste inputs) are required to produce 1,000 lb (454 kg) of new PS. Therefore, to depict the net impacts from recycling the 41 tonnes of waste PS in S1, the emissions from the production of 75 tonnes of virgin PS material are subtracted from the emissions associated with the production of the same amount PS material with 50 % recycled content. Section S-4.4 of the Supplementary Material lists the percent diversion of each residential waste stream in the City of Toronto, the unit processes selected to depict recycling, and the reprocessing efficiencies of each recycling process.

4.2.5 Landfilling

Toronto's residential waste in 2008 was disposed of at a sanitary landfill in Carleton Farms, Michigan and at the Green Lane landfill near St. Thomas, Ontario. Approximately 93 % of the residual waste tonnage was sent to the former, which is more than double the distance from Toronto than that of the Green Lane landfill (City of Toronto 2010a). The *US-EI* sanitary landfilling unit process models the short-term (less than 100 years) and long-term (up to 60,000 years) transfer coefficients of the chemical elements within the landfilled waste (Doka 2009). The differing waste inputs associated with each waste management scenario affect the magnitudes and timing of emissions through the seven stages of landfill development that can be discerned in the model (Doka 2009). Uncertainties associated with the potential impacts of landfilling reflect the inherent variability of landfilling processes, which are influenced by waste composition, landfill design and operation, climate, and topography.

Both landfills possess equipment to collect the landfill gas emitted from the decomposition of waste. The collected gas, composed of approximately 50 % methane, is assumed to be 53 % of total emissions (Doka 2009). The quantity of displaced electricity from the utilization of the collected gas reflects (1) the 6.4 MW_e electrical capacity of the generators at the Carleton Farms landfill (Landfill Energy Systems n.d.), (2) an assumed 80 % capacity factor for the generators, based on Shin et al. (2005), (3) an assumed 30 % energy conversion efficiency (Mohareb et al. 2008), and (4) the estimated 37 % of total type II (residential) waste sent to the Carleton Farms landfill in 2008 that was from the City of Toronto. The 37 % estimate is based on (1) the total volume of 3,475,174 yd³ of type II waste landfilled at Carleton Farms Landfill in 2008 (G. Morrow, pers. comm.); (2) the conversion factor of 0.356 t/yd³ of compacted mixed MSW (US EPA 1994); and (3) the tonnage of Toronto's MSW shipped to the landfill in 2008. These electricity production assumptions are also extrapolated to conditions at the Green Lane landfill, leading to an overall estimated displaced electricity of 5.38×10⁶ kWh for the 2008 reference scenario, and 5.29×10⁶ kWh for the waste prevention scenario.

4.2.6 Reuse of wine and spirit containers

Wine/spirit container reuse requires bottle washing, as well as shipment to and from bottle washing/refilling facilities. A 200 km estimate is used as a plausible round-trip distance to transport the empty glass bottles (i.e., approximately the round-trip distance between Toronto and the Niagara wine region between Stoney Creek and Niagara on the Lake). Technical data for a bottle washing LCA process depicting the use of modern equipment for 1,000-ml glass wine

containers were provided by a bottle washing equipment manufacturer (Cleary 2013).

5 Life cycle impact assessment results

The LCA results indicate that the waste prevention scenario is superior to the reference scenario for all midpoint and endpoint level indicators (Fig. 2, Table 3, Table S-10 of the Supplementary Material). For the 2008 reference scenario, 6/18 of the midpoint level indicators depict net avoided impacts, rising to 9/18 under the waste prevention scenario. For the endpoint level results, the ecosystem quality indicator for S1 shows a net avoided impact, while for S2, a net avoided impact is present for both the ecosystem quality and resource availability indicators. The greatest contributors to the human health endpoint level impacts are climate change and human toxicity. Similarly, climate change is also responsible for the largest portions of the ecosystem quality impacts for both scenarios, although the reduction in agricultural land occupation more than compensates for these climate change impacts. The natural resource use impact, comprising metal depletion and fossil fuel depletion, is almost entirely influenced by the latter.

The presence of both impacts and avoided impacts within the S1 and S2 life cycles makes it appropriate to use absolute impact magnitudes to examine the relative impact contributions of each stage of these life cycles. For each LCA scenario, the recycling and landfilling stages tend to dominate the absolute midpoint level impacts, with the former almost always responsible for net avoided impacts, and the latter contributing mainly to toxicity and eutrophication impacts (Table S-10, Fig. S-1, and S-2 of the Supplementary Material). At the endpoint level, recycling dominates for the ecosystem quality and resource availability indicators, while landfilling provides the greatest contribution to the human health impact (Fig. 3).

The endpoint level results of the 2008 reference scenario illustrate the importance of recycling (20–58 % of absolute endpoint level impacts) and landfilling (8–57 %) within the life cycle of waste, and challenge the claim that the environmental burdens from waste collection/transportation (9–41 %) are negligible in comparison with waste treatment (e.g., Mendes et al. 2004). For the resource availability indicator, waste collection and transportation have considerably larger impacts than landfilling. Other than the displaced electricity associated with the combustion of landfill gas, the biological treatment system provides the smallest contribution of impacts (2–5 %) for all endpoint level impact categories but one (ecosystem quality). Nevertheless, this small contribution does not recognize the role of biological treatment in reducing landfilling impacts. Unlike the other life cycle components,

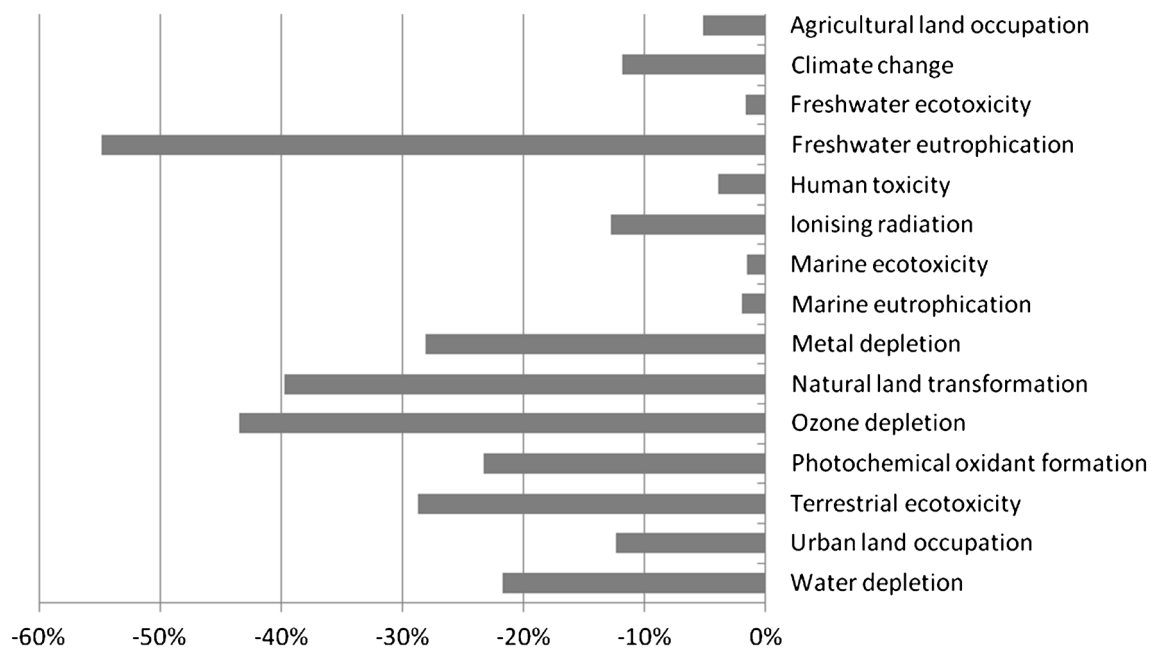


Fig. 2 Net percent difference between the waste prevention scenario and the 2008 reference scenario for midpoint level environmental impacts under the *ReCiPe (H)* LCIA method. Note: the net impacts of the

terrestrial acidification, particulate matter formation, and fossil depletion indicators become net avoided impacts (not shown in figure)

recycling and the displaced electricity due to the use of landfill gas are responsible for a net avoided impact.

The tonnage of waste prevention undertaken in S2 is equivalent to only 3.6 % of the tonnage of waste collected in the reference scenario. Thus, it is not surprising that the downstream components of the waste management system have a greater absolute impact contribution than those upstream (Fig. 3). Yet, the net upstream benefits of these WPAs are always proportionally greater than the percent mass reduction would suggest (Note: the grasscycling WPA has only downstream benefits), reaching between 6 and 13 % of the absolute endpoint level impacts associated with S2.

The upstream avoided impacts associated with the WPAs exceed the endpoint level impacts from the collection and biological treatment of all of the residential waste in Toronto. Among the various WPAs, the net upstream benefits from the prevention of admail and conventional wine and spirit containers provide the greatest contributions to reducing impacts. Other than grasscycling, the disposable bag WPA tended to have the smallest upstream effect on the waste management system. The grasscycling WPA had only downstream effects,

which comprised a very small portion of the waste collection (<1 % by tonnage), transportation (<1 % reduction in tonne-km), and biological treatment (<5 % reduction in organic waste inputs) components of the life cycle.

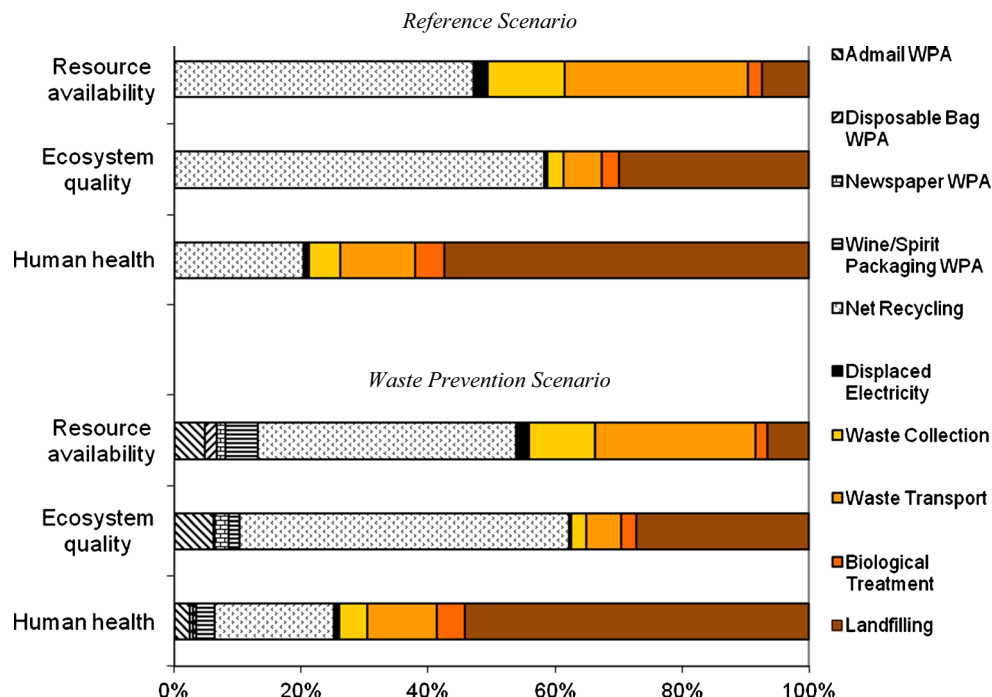
In S2, all of the WPAs are responsible for net avoided endpoint level impacts (Table 4). The substitute product services, when present, always cause lower net impacts than the product services they are replacing. Downstream, waste prevention reduces the overall impacts from waste collection, transportation, and treatment, by an average of 2 %. However, the WPAs also reduce the tonnage of waste that is recycled and the amount of electricity generated from landfill gas combustion, thus diminishing their potential benefits. The net benefits from recycling decrease by 3 % for the natural resources indicator, and by 4 % for both the human health and ecosystem quality indicators. Furthermore, there is a 2 % mean decrease in displaced electricity due to the reduction in landfilled waste. In all cases, the upstream reduction in impacts more than compensates for the increased impacts from the changes in recycling and displaced electricity.

Table 3 Net endpoint level impacts from the 2008 reference and waste prevention scenarios

Endpoint level impact indicator	2008 reference net impact	Waste prevention scenario net impact	% reduction
Ecosystem quality	−1.27 species.yr	−1.97 species.yr	55 %
Human health	5.18×10 ² DALY	4.53×10 ² DALY	13 %
Natural resources	\$1.35×10 ⁷	−\$1.29×10 ⁸	−961 % (from impact to avoided impact)

DALY disability adjusted life years

Fig. 3 Life cycle components of each scenario as a percent of the sum of the absolute values for the endpoint level indicators. For all impact categories, the WPAs, net recycling, and displaced electricity components are responsible for net avoided impacts, while the waste collection, waste transport, biological treatment, and landfilling components are responsible for environmental damage. “Waste collection” depicts the impacts from transporting the waste to the waste transfer stations. “Waste transport” signifies transporting the waste from the transfer stations to the treatment facilities



The results in Table 4 also illustrate the importance of the selected system boundary in defining the relative benefits from the WPAs, which are curtailed considerably if a traditional system boundary for an LCA of waste is maintained (i.e., no upstream expansion of the system boundary for the WPAs). For two of the three endpoint level indicators (ecosystem quality and natural resources), the WPAs are responsible for net increases in downstream impacts. These results reveal that the reduction in gross downstream impacts (e.g., waste transportation, landfilling) does not compensate for the increase in impacts from the recycling and displaced electricity components of the life cycle.

6 Sensitivity analysis

A sensitivity analysis is undertaken to examine the impacts of varying (1) the levels of recycled content in the goods

subject to waste prevention, (2) the life cycle impact assessment (LCIA) perspectives used for calculating the endpoint level indicators, and (3) the LCIA method employed. If it is assumed that the materials subject to waste prevention (newsprint, HDPE plastic film, PET bottle, and container glass) contain no recycled content, overall net avoided impacts increase by up to 11 %, while the net avoided upstream impacts rise by up to 14 % (Table 5). If the materials are to be composed entirely of recycled content, overall net avoided impacts fall by up to 27 %, while upstream avoided impacts are reduced by up to 24 %. The effect on the natural resources indicator is generally greater relative to the others because the upstream WPA components comprise a larger proportion of the natural resource impacts (Fig. 3). It should be noted that the 100 % recycled content assumption is not reflective of existing recycling processes because there is always some loss during processing, and/or the need to incorporate some virgin content.

Table 4 Net endpoint level impacts of each WPA within the waste prevention scenario

Endpoint level impact indicator	Upstream effect in waste prevention scenario				Downstream effect relative to reference scenario		
	Admail WPA	Disposable bag WPA	Newspaper WPA	Wine/spirit packaging WPA	Change in gross downstream impacts	Additional net impact of recycling	Reduced benefit of displaced electricity
Ecosystem quality (species-yr)	-4.85×10^{-1}	-1.66×10^{-2}	-1.66×10^{-1}	-1.39×10^{-1}	-6.42×10^{-2}	1.68×10^{-1}	5.61×10^{-4}
Human health (DALY)	-2.32×10^1	-3.24	-4.85	-2.80×10^1	-1.36×10^1	7.18	1.36×10^{-1}
Natural resources (\$)	-5.32×10^7	-2.18×10^7	-1.54×10^7	-5.55×10^7	-1.24×10^7	1.51×10^7	3.62×10^5

Table 5 Endpoint level net avoided impacts of the waste prevention scenario when the prevented materials contain no recycled content and 100 % recycled content

Endpoint level impact indicator	“No recycled content” net impact	% decrease in impact/ increase in avoided impact	% increase in upstream avoided impact	“100 % recycled content” net impact	% increase in impact/ decrease in avoided impact	% decrease in upstream avoided impact
Ecosystem quality (species·yr)	−2.09	5.7 %	13.9 %	−1.80	8.6 %	21.1 %
Human health (DALY)	4.47×10^2	1.2 %	9.4 %	4.62×10^2	2.0 %	15.4 %
Natural resources (\$)	-1.43×10^8	10.8 %	9.6 %	-9.46×10^7	27.0 %	23.9 %

ReCiPe groups the uncertainties associated with some of its impact conversion and aggregation measures into “perspectives” (egalitarian—*E*, hierarchist—*H*, individualist—*I*) (Goedkoop et al. 2009). When adopting the *E* and *I* perspectives for S2, the magnitudes of the changes in net impacts relative to the *H* perspective are substantial, especially for the human health (2 to 10 times the magnitude) and ecosystem quality (0.1 to −3 times the magnitude) endpoint indicators. Nevertheless, the relative proportions of the absolute impacts attributed to the WPA component of the waste management system are similar to the results when using the hierarchical perspective (Section S-6, Supplementary Material).

Comparing results using different LCIA methods is useful in order to provide an indication of the uncertainty associated with the LCIA stage of the study. This uncertainty is derived, in part, from the inconsistency in the selection and design of the impact categories (e.g., during the impact characterization stage, the LCIA methods may not assign the same weights to inventory values within each midpoint level impact category). *ReCiPe* and *TRACI 2.1* share some impact categories in common, although *TRACI 2.1* lacks indicators for categories such as land use, water, and metal depletion. Overall, the S1 and S2 results are identical for global warming potential, but 35–44 % higher for the *TRACI 2.1* ozone depletion indicator (Section S-6, Supplementary Material). The remaining indicators are not directly comparable. Nevertheless, the proportions of the absolute impacts attributed to the various components of the waste management system may be estimated in order to compare their relative importance within the life cycle. When adopting this means of comparison, one observes that the proportion of the absolute impacts of S2 that is ascribed to the WPAs is very similar for a number of indicators, including global warming/climate change, ozone depletion, fossil fuel depletion and smog/photochemical oxidant formation (Section S-6, Supplementary Material). The WPAs are responsible for between 0 and 19 % of the absolute midpoint level impacts when using *ReCiPe*, and between 0–14 % of those impacts when using *TRACI 2.1* (Section S-6, Supplementary Material).

7 Discussion

The results from this LCA demonstrate that the introduction of waste prevention activities improved the environmental performance of the waste management system despite impact increases from diminished recycling and displaced electricity. Moreover, the impact reductions could be achieved without compromising the quantity of product services consumed by municipal residents.

The methodological choice of incorporating the changes in the upstream processes of each WPA helped to ensure that a small reduction in waste prevention provided a disproportionate benefit to the entire MSW management system. For example, the reductions in impacts were considerably larger than the percentage decrease in the tonnage of waste collected. In contrast, the results in Table 4 demonstrate that the alternative option of excluding any upstream benefit of waste prevention from the LCA of waste would sometimes result in net increases in impacts.

The initiatives evaluated in S2 are either currently being pursued, or have been under consideration, such as the refilling of wine bottles (e.g., Leighton 2010). Waste prevention through plastic bag reuse, grasscycling, and online newspaper reading can be facilitated through education campaigns and financial incentives. Other means of waste prevention, such as admail opting out schemes and bottle refilling programs, often require additional institutional support. Waste prevention can also be initiated at the product design stage, through lightweight packaging design, for example. However, unlike the WPAs modeled within S2, initiatives to reduce the production of waste are often nonproduct specific. For example, residents of Toronto are charged more if they wish to use a larger container for their residual waste (City of Toronto n.d.), thus decreasing the real income of residents should they choose to generate greater amounts of waste. In contrast, the municipality charges nothing for larger containers for recyclable material.

The sensitivity analysis highlighted the potential environmental gains from targeting WPAs at those waste streams that possess low levels of recycled content. Nevertheless, in no

cases did the prevention of goods, even with a hypothetical 100 % recycled content level, result in a worse environmental performance for the waste management system (relative to the 2008 reference scenario).

The results from this LCA also point to additional gains from targeting WPAs at products that are landfilled because no potential recycling benefits would be eliminated, although landfill gas generation would be curtailed. For this case study, the increases in impacts from displaced recycling were greater than those associated with the reduction in landfill gas utilization.

Although the system boundary of this LCA is expanded to incorporate the benefits from the displacement of material and electricity production, additional cascading and rebound effects may also be considered (Hertwich 2005; Gentil et al. 2011). Supplementary system expansions can be used to contribute more detailed information on the consequences of introducing WPAs to waste management systems. However, they would also considerably augment the uncertainty of the results, as well as cause modeling difficulties due to the many potential behavioral and system responses to changes in costs and resource availability (Hertwich 2005; Thiesen et al. 2008).

8 Conclusions

The results of this case study are in keeping with the assumption inherent in the waste hierarchy that waste prevention has a superior environmental performance relative to the various waste treatment options. Environmental benefits can be augmented by focusing waste prevention policies on waste materials currently allocated to landfills and those containing low levels of recycled content. These promising results for waste prevention indicate that further research into the potential of WPAs to reduce the life cycle effects of residential waste management is merited.

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